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Request for grant of a patent

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1. Your reference	AMS.P52287GB	
2. Patent application number *(The Patent Office will fill in this part)*	0222524.1	27 SEP 2002
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	WesternGeco Seismic Holdings Limited Citco Building PO Box 662 Road Town Tortola, British Virgin Islands	
Patents ADP number *(if you know it)*	08472147001	
If the applicant is a corporate body, give the country/state of its incorporation	British Virgin Islands	
4. Title of the invention	Calibrating a Seismic Sensor	
5. Name of your agent *(if you have one)*	Marks & Clerk	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	4220 Nash Court Oxford Business Park South Oxford OX4 2RU United Kingdom	
Patents ADP number *(if you know it)*	7271125001	

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
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Yes

Patents Form 1/77

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Continuation sheets of this form	0
Description	6
Claim *(s)*	0
Abstract	0
Drawing *(s)*	2

10. If you are also filing any of the following, state how many against each item.

Priority documents

Translations of priority documents

Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*

Request for preliminary examination and search *(Patents Form 9/77)*

Request for substantive examination *(Patents Form 10/77)*

Any other documents *(please specify)*

11.

I/We request the grant of a patent on the basis of this application.

Signature Mark a Clerk Date

Marks & Clerk 27 September 2002

12. Name and daytime telephone number of person to contact in the United Kingdom

Dr Andrew Suckling
(01865) 397900

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Calibrating a Seismic Sensor

The present invention relates to calibrating a seismic sensor. It is particularly applicable to use with multi-component seismic data.

Realizing the full value of multi-component seismic recordings requires calibrating such data for the effects of inconsistent geophone coupling and instrument response. Calibration of the vertical component of particle velocity against the pressure (P/v_z-calibration) is commonly based on the up- and down-going wavefields in the water layer, which can be computed from an angle-dependent summation of P and v_z. One approach to P/v_z-calibration is to require seismic energy to be preserved during propagation through the water layer. In this case, frequency- and wavenumber-dependent calibration operators are designed by means of spectral balancing of the up- and down-going wave components just above the seafloor. Another approach to P/v_z-calibration is to identify data windows containing exclusively up- or down-going events and subsequently minimise the energy of the computed down- or up-going energy, respectively.

Prior art

It is commonly assumed that the hydrophone is perfectly coupled to the fluid medium and that the pressure is therefore a good representation of compressional wave reflectivity. On the other hand, the geophone recordings (v_x, v_y, v_z) suffer from the effects of inconsistent coupling, incorrect orientation and differences in instrument response, and thus need to be calibrated against the hydrophone data.

Existing P/v_z-calibration techniques are based on the up- and down-going components of the pressure just above the seafloor, P^- and P^+, which can be expressed as:

$$P^{\pm}(f,k) = \frac{1}{2}P(f,k) \pm \frac{\rho}{2q(f,k)}a(f)v_z(f,k), \qquad (1)$$

respectively, where P is the pressure, v_z is the vertical velocity component, f is the frequency, k is the horizontal wavenumber, ρ is the density of water, q is the vertical slowness in the water layer and $a(f)$ is the unknown calibration filter that corrects for imperfections in the recordings of v_z.

One strategy for determining $a(f)$ is to identify data windows containing exclusively up- or down-going waves and subsequently minimize the down- or up-going pressure in these windows in a least-squares sense. K.M. Schalkwijk et al. proposed, in "Application of Two-Step Decomposition to Multicomponent Ocean-Bottom Data: Theory and Case Study", J. Seism. Expl., 8, 261-278 (1999), designing the calibration filter $a(f)$ by minimizing the energy of the down-going pressure in a window containing primary reflections only, whereas Van Manen and Melboe (patent application, 30 October 2001) proposed a similar approach using a data window containing critically refracted waves. The latter technique is more suitable for automation using first-break pickers, allows application to data acquired in shallow seas and makes use of clean, unclipped data. Once the calibration filter $a(f)$ is determined, it can be applied to the entire data set.

Ball and Corrigan (1995) suggested calibrating the vertical geophone data against pressure by applying a hydrophone ghost operator to v_z and a geophone ghost operator to the pressure. It can be shown that this approach is equivalent to predicting the down-going pressure from the computed up-going pressure. Minimising the difference between the predicted and the computed down-going pressure at times larger than source duration plus the one-way propagation time through the water layer then allows the desired calibration filter to be determined. An important drawback of this technique is the need for accurate information about the water depth in the survey area.

The present invention provides a method of calibrating a seismic sensor in the common shot domain. The invention may be used, for example, to calibrate a geophone relative to a hydrophone.

Coupling and instrument response variations are receiver-consistent effects and therefore geophone calibration is usually performed in the common-receiver domain (CRD). However, we have realized that optimising the vector fidelity of a seismic sensor such as a multi-component geophone in the common shot domain (CSD) has considerable advantages:

- Unlike CRD processing, CSD processing does not implicitly assume the sub-surface to be laterally invariant.
- Rough sea perturbations can properly be accounted for.
- We can benefit from the dense receiver spacing if the source-side spacing is coarser.
- Waterborne noise that is not shot-generated can be removed more efficiently.

This invention describes how to formulate P/v_z-calibration techniques so that they can be applied in the common-shot domain. The new formulations do not only benefit from the advantages associated with CSD-processing, but also feature improved stability and facilitate the use of numerically efficient filter approximations.

In one embodiment, the method comprises minimising the energy of a selected constituent of seismic data, and this may be done for a pre-determined range.

In another embodiment, the method comprises minimising the imbalance between up-going seismic energy and down-going seismic energy, or between the up-going constituent of a component of seismic energy (such as, for example the vertical velocity component) and the corresponding down-going constituent. This is preferably done after muting the direct wave.

The invention will be described by way of illustrative examples with reference to the accompanying Figures in which:

Figure 1 is a schematic flow diagram of a first embodiment of the invention; and

Figure 2 is a schematic flow diagram of a second embodiment of the invention.

Description of the invention

Geophone coupling is a receiver-consistent effect, i.e. the required calibration operator is constant for each geophone and does not depend on the shot position. As mentioned above, existing P/v_z-calibration techniques are based on the computation of the up- and down-going components of pressure in the water layer (eq. 1). Unfortunately, this involves a spatial filter operation over the vertical component of particle velocity, which complicates the computation of the unknown calibration filters. Performing the techniques in the common-receiver domain, i.e. computing the spatial Fourier transform over source locations, allows determining the calibration filters separately, but suffers from the drawbacks mentioned in the summary.

On the other hand, the up- and down-going vertical components of particle velocity in the water layer can be expressed as:

$$V_z^{\pm}(f,k) = \frac{1}{2} a(f) v_z(f,k) \pm \frac{q(f,k)}{2\rho} P(f,k). \qquad (2)$$

The computation of these wave components involves spatial filtering of pressure instead of v_z. As a result, the filter operation in the above equations does not interact with the unknown calibration filters *a(f)* when applied in the common shot domain and thus greatly facilitates performing the calibration in the CSD. Furthermore, the operators in equation (1) contain a pole, whereas the operator in equation (2) contains a zero. As a result, techniques based on equation (2) are numerically more stable and facilitate the use of spatially compact filter approximations. The latter feature may be important in areas with strong lateral sub-surface variations.

In the following two embodiments of the invention, we will explain in detail how to formulate two P/v_z-calibration techniques such that they are suitable for CSD-processing. However, note that a similar procedure also can be carried out for P/v_x-

calibration as proposed by Schalkwijk et al. (1999), provided that the elastic properties of the seabed are known.

Example 1: P/v_z calibration using up-going waves

Based on the above observations, the P/v_z calibration techniques proposed by Schalkwijk et al. (1999) and Van Manen and Melbø (2001) can be modified to allow for CSD-processing. In this embodiment frequency-dependent calibration filters can be designed by minimising the energy of v_z^+ over a data window containing critically refracted waves only. This approach involves the following processing steps (see flowchart in Figure 1):

1. Sort the pressure recordings in shot gathers and transform the pressure recordings to the fk or tau-p domain.
2. Carry out the spatial filtering $\frac{q(f,k)}{2\rho}P(f,k)$ (over receivers and subsequently iterate over all shots).
3. Inverse transform the filtered result to fx, tau-x or tx space and sort into receiver gathers.
4. Design the calibration filter $a(f)$ for each receiver separately by minimising equation (2) over a data window containing exclusively up-going events, such as primary reflections or critically refracted waves.
5. Apply the calibration filters $a(f)$ to the recorded vertical geophone data.

Example 2: Spectral balancing of up- and down-going wavefields

Another approach to P/v_z-calibration in the common shot domain is based on the observations that the water layer is non-attenuative for seismic waves and that the free surface has a known constant reflection coefficient r_0. As a result, all up-going energy in the water layer should be recorded as down-going energy at some later time reduced by a factor r_0. The direct wave represents an exception to this criterion, as that event cannot be predicted from the up-going wavefield. Receiver-consistent and frequency-

dependent calibration filters can be designed by means of spectral balancing of the down-going energy, preferably after muting of the direct wave with the up-going energy. This can be achieved by minimisation of a suitable objective function such as, for example, the following objective function:

$$E = \sum_{f,k} W(f,k)\left(\left|V_z^-(f,k)\right| - \left|V_z^{(r)+}(f,k)\right| \right)^2, \tag{3}$$

where $W(f,k)$ is a weighting function specifying the frequency-wavenumber window over which to perform the optimisation, v_z^- is the up-going vertical component of particle velocity in water and $v_z^{(r)-}$ corresponds to the down-going vertical component of particle velocity in the water after muting of the direct wave. A flow-chart for this embodiment of the P/v_z-calibration technique is shown in Figure 2.

The main advantages of this approach to P/v_z-calibration include:

1. The problem is formulated completely independent of the water depth. As such, this methodology is applicable to data acquired over both shallow and deep seas.
2. User-defined input (such as picking of data windows) is avoided, rendering the technique more suitable for automation.
3. P/v_z calibration is performed on the basis of the entire data set instead of a small subset of data. We anticipate that this feature is beneficial for the both the stability and accuracy of the designed calibration filters.
4. The method is readily applicable in the common shot domain, since minimisation of equation (7) requires spatial filtering of hydrophone recordings only. In this case, the spatial filter can be applied to the pressure in the common shot domain after which the filtered output can be resorted into receiver gathers for efficient computation of the calibration filters $a(f)$ as described in the previous section.

A method according to the invention may be carried out using a computer or other data processor programmed to perform the method. A program for controlling a computer to perform a method according to the invention may be stored on any suitable data carrier, such as a magnetic or optical data carrier.

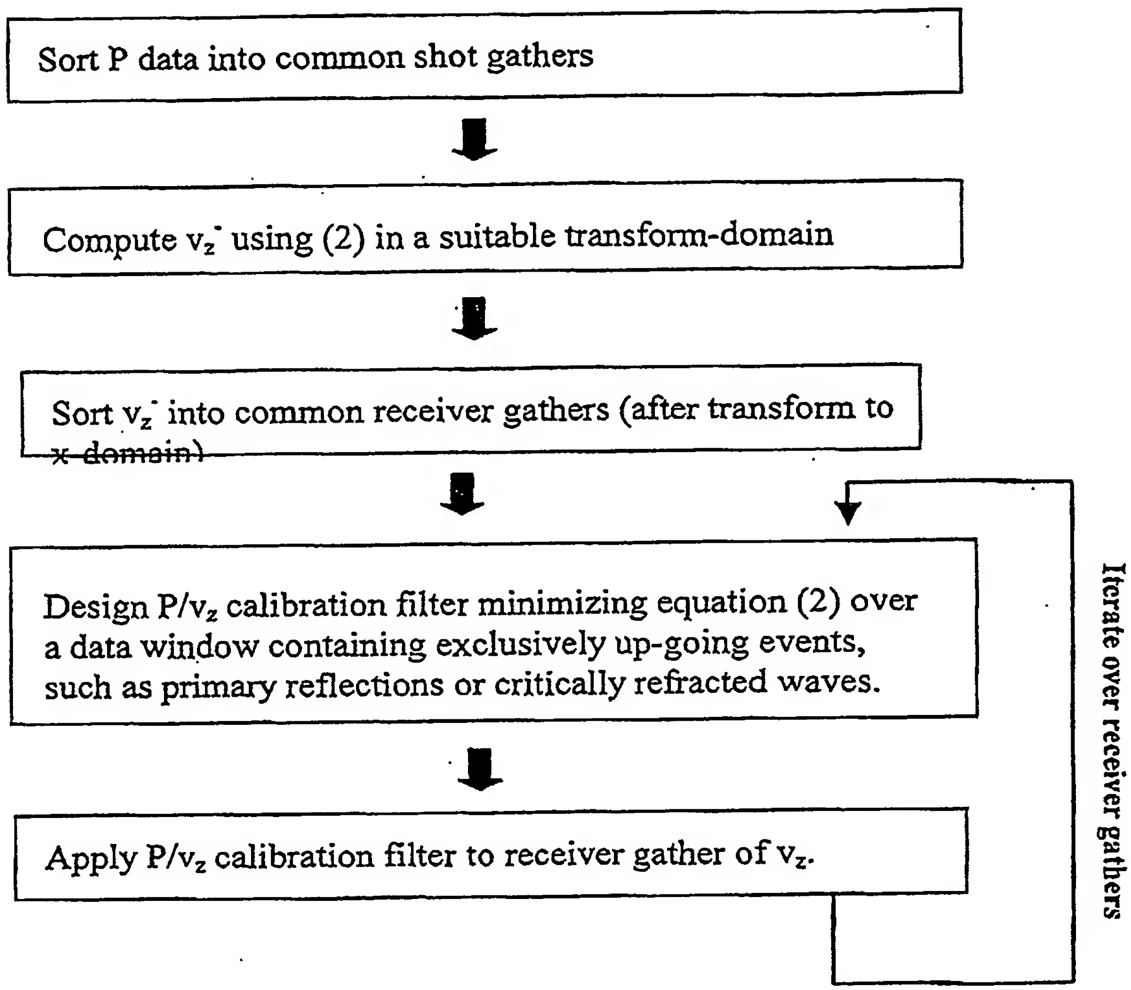

Figure 1: Flowchart for the proposed P/v_z calibration technique using up-going waves (Example 1).

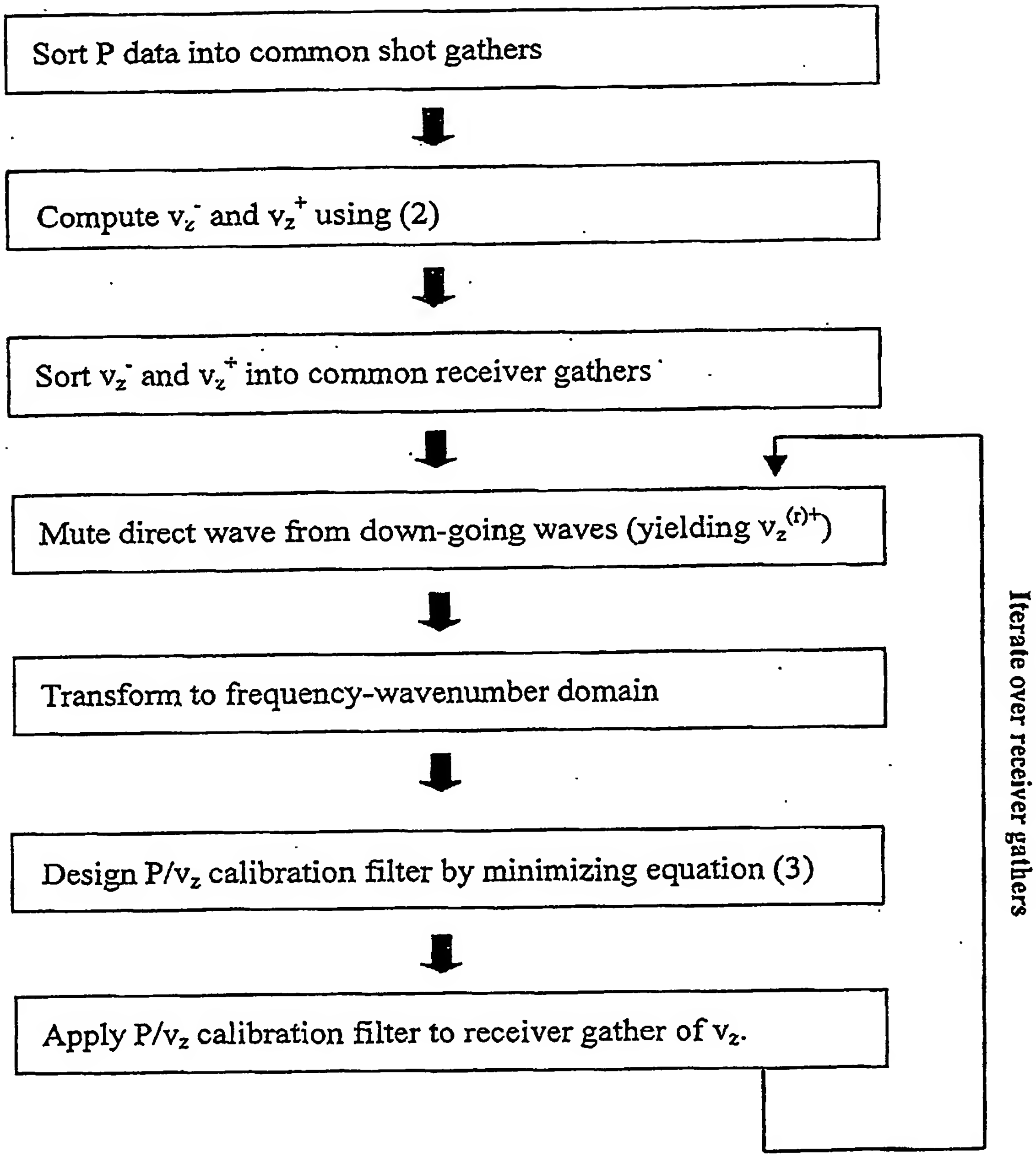

Figure 2: Flowchart for the proposed P/v_z calibration technique based on spectral balancing of up- and down-going wavefields (Example 2).